Transmission Magnetization Imaging Using the STXM

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INTRODUCTION

As nano-scale magnetic structures, including both ultrathin films and laterally confined structures, become more important in technology, so does the need to image their magnetization behavior. Many issues associated with magnetic structure, interactions between phases, and dynamics of reversal processes must be understood at relevant length scales in these structures [1]. Several common methods for imaging magnetization include visible magneto-optical techniques, magnetic force microscopy, and a variety of electron techniques including transmission, scanning, and imaging microscopy. Each has advantages and limitations, and together they should be considered as complementary and used to best advantage for specific problems. Following initial demonstration of magnetization imaging using the scanning transmission x-ray microscope (STXM) on beamline 7.0 we have continued to investigate these capabilities and how they complement other techniques to image magnetization.

Unique capabilities of magnetic microscopy using soft x-rays result from the strong contrast mechanisms inherent in large magnetic circular dichroism (MCD) [2] and magneto-optical rotation [3] at $L_{2,3}$ edges of the 3d transition metals. These large resonant magneto-optical effects lead to both elemental sensitivity and sensitivity to a relatively small number of spins. Photon-based soft x-ray microscopes (photon-in, photon-out) have advantages resulting from the ability of photons to penetrate well into samples to image magnetization in buried layers and at buried interfaces, as well as insensitivity to applied fields to allow for field-dependent imaging [4]. Two important capabilities of photon-based soft x-ray microscopes are illustrated below.

Direct contrast to magnetization is currently obtained in the STXM as absorption contrast through the MCD effect, by placing a saturated magnetized film upstream to create a circular polarizing filter [5, 6]. When tuned to the L_3 peak of Fe, Co or Ni the incident linearly polarized beam is converted to an elliptically polarized beam by preferential absorption of one of the two circular components with opposite helicity. Such circular filters are essentially Faraday effect modulators in the soft x-ray range. Reversing the magnetization in the filter reverses the helicity of the transmitted elliptical polarization. In both circular filter and magnetic sample the magneto-optical effects are proportional to $\boldsymbol{k} \cdot \boldsymbol{M}$ where $\boldsymbol{k}$ is the wave vector and $\boldsymbol{M}$ the magnetization.

VECTOR IMAGING OF MAGNETIZATION THROUGH TILTING

The relatively long working distance of the STXM allows sample tilting through large angles. Since most thin magnetic films have $\boldsymbol{M}$ in plane, tilting away from normal incidence is generally necessary to obtain magnetic contrast. Figure 1 demonstrates other advantages of tilting. All images are of the same region of a 33 nm Fe film containing a domain wall between 180°

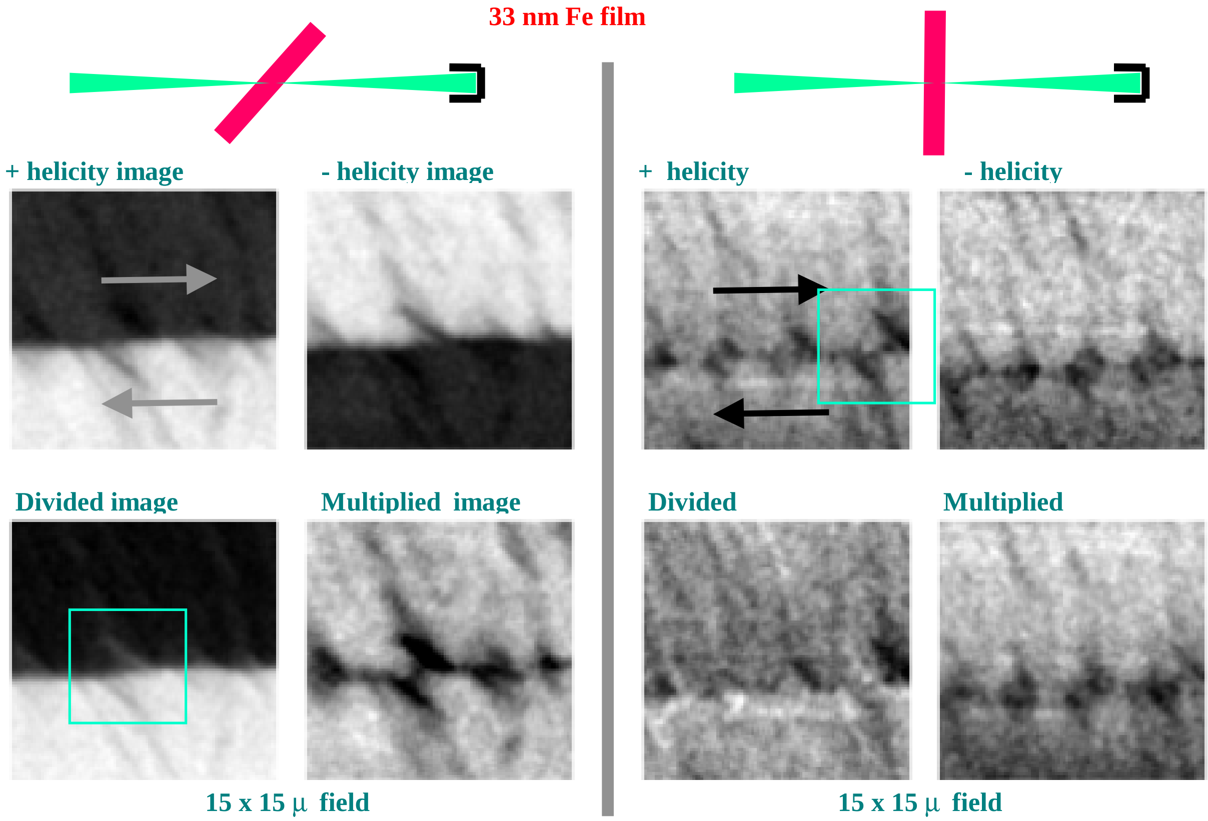

Figure 1. Transmission magnetization images across a domain wall between 180° domains in a 33 nm thick Fe film. Images at left are obtained at 45° grazing incidence while those at left are obtained at normal incidence. The squares indicate what are believed to be the same loction in the sample in the two different views.

domains having magnetization nominally along the arrows. At left are four images obtained from data taken at 45° from grazing and at right are corresponding images taken at normal incidence. The top two images show transmitted intensity obtained using incident + and – helicity elliptically polarized radiation, and the bottom contains the division and multiplication of these images. Divided images enhance magnetic contrast between regions with fixed magnitude of $\boldsymbol{k} \cdot \boldsymbol{M}$, while multiplied images enhance regions where $\boldsymbol{k} \cdot \boldsymbol{M}$ varies away from this average. Much structure in $\boldsymbol{M}$ is evident both along the domain wall and extending away from the wall into the domains. Normal incidence images reveal unambiguously that normal components of $\boldsymbol{M}$ are associated with domain walls in this film, and that these normal components form well-defined structures periodically positioned along the wall. Domain walls in soft magnetic films are of Bloch type ($\boldsymbol{M}$ rotates mostly out of film plane across wall) for large thickness and Neél type ($\boldsymbol{M}$ rotates mostly within film plane across wall) for small thickness. This specific sample is of intermediate thickness and shows both Bloch and Neél character; such hybrid wall structures are known as cross-tie walls. The ripple structure extending into the domains from the walls also shows normal $\boldsymbol{M}$ components and clearly originates at the Bloch lines that are spaced roughly 4 microns apart along the wall. These heterogeneities in magnetization structure relate directly to the magnetization reversal mechanism for this demagnetized film.

Many magnetic nanostructures may contain 3-dimensional components to their magnetization, like this simple system of a thin Fe film. While the origin of possible 3-dimensional magnetization may vary from system to system, the ability to image and quantify the full vector magnetization in small samples is generally important. The simple $\boldsymbol{k} \cdot \boldsymbol{M}$ contrast readily provides numerical algorithms to determine the vector components of magnetization along the different directions viewed. With three viewing angles the full vector dependence of $\boldsymbol{M}$ can be measured.

DIRECT IMAGING OF MAGNETIZATION IN EXCHANGE-COUPLED BILAYERS

A uniquely powerful capability of photon-out magnetization imaging with soft x-rays is the ability to penetrate overlayers that may be magnetic and image magnetization in buried layers. This is demonstrated in Figure 2. The sample in this case is a demagnetized sandwich structure consisting of Fe and Co films separated by a thin SiC spacer layer. The circular polarizer is a similar bilayer structure, providing MCD contrast at each elements L_3 edge. At left is a divided image taken at the Fe edge and at right a divided image taken at the Co edge. The large 180° domains of the single Fe film are absent in this bilayer structure, and instead we see much smaller, less regular features in the Fe magnetization. Similar features are seen in the Co magnetization. It is apparent that there exists partial but not complete spatial correlation of the magnetization distribution in the Fe and the Co layers. These images reveal that interactions between the two magnetic layers through the spacer layer can influence static magnetization distribution in each layer, as well as the magnetization reversal mechanism.

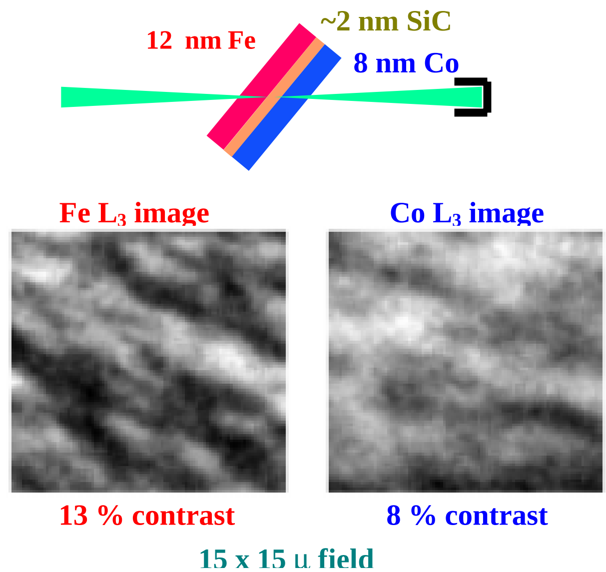

Figure 2. Transmission images of magnetization distributions in thin Fe and Co layers separated by a SiC spacer. Images obtained with opposite helicity elliptical polarization are divided to produce these images.

CONCLUSIONS AND FUTURE DIRECTIONS

The ability of photon-based soft x-ray microscopy techniques to study magnetic layers buried beneath other (possibly magnetic) layers offers important complementary capabilities to other magnetic imaging techniques. In particular, the ability to image non-destructively the magnetization in different, interacting layers of structures opens up many possibilities in the study of interactions between different magnetic phases in nano-scale structures. In the coming year we plan to implement an electromagnet that will enable field-dependent imaging of reversal processes at low fields. Alternatively we should be able to measure spatially resolved hysteresis loops from different parts of samples.

Clear limitations are evident in our scheme for magnetic imaging requiring polarizing filters to obtain MCD contrast. The Faraday effect filters function over only very limited bandwidths centered on strong white lines of ferromagnetic elements exhibiting MCD. The limited bandwidth precludes measurement of the full MCD spectrum of the sample that can provide important information regarding spatially varying chemical state effects and orbital and spin moment information from sum rules. The strong absorption in the filter reduces intensities by roughly an order of magnitude, thereby increasing the difficulty of imaging weak magnetization features. The implementation of a scanning x-ray microscope on an elliptically polarizing undulator would significantly enhance the capabilities of the current microscope. We are also considering how other contrast mechanisms, such as magneto-optical rotation, can complement current capabilities. A reflection (Kerr) microscope using polarization and/or intensity analysis of reflected beams for contrast would greatly increase the number of samples and scientific problems that could be addressed. Together with variable applied fields and control of sample temperature, these capabilities form the basis of a conceptual design for an advanced scanning x-ray microscope that would take maximum advantage of unique attributes of soft x-rays for imaging magnetization.

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